Adhesive strength of flame-sprayed polymer coatings

Cite as: AIP Conference Proceedings **1785**, 030011 (2016); https://doi.org/10.1063/1.4967032
Published Online: 18 November 2016

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Adhesive Strength of Flame -Sprayed Polymer Coatings

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Abstract. Flame spraying of polymers allows obtaining functional coatings for protecting against wear and corrosion. Adding different fillers to the original powdered polymer material allows the properties of the coatings to be intentionally changed. The durability of coatings is mainly determined by their adhesive strength. The aim is to study the influence of some characteristics on the adhesive strength of coatings applied to the flame spraying of polymers. The characteristics include the type of original polymers, the particle size, the share of inorganic fillers, and the oxidizer-to-fuel ratio of the flame.

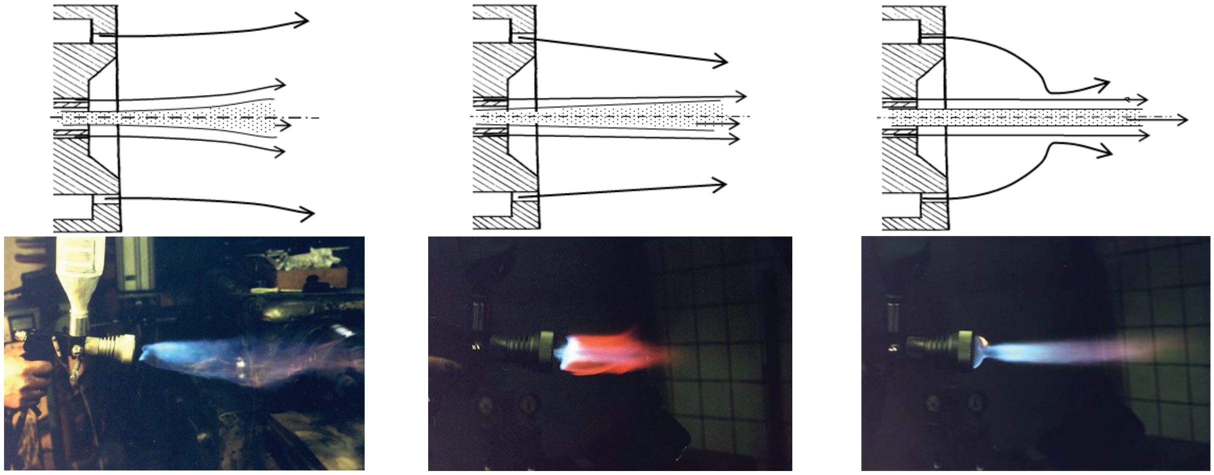
INTRODUCTION

One of the most economical and easiest-to-implement methods of spraying a polymer coating are methods of thermal technology. In particular, flame spraying allows melting and forming a layer in a single operation. Since 1970s, guns of "oxygen/air – acetylene/propane combustion mixtures are used for flame spraying of polymer materials [1–4]. The guns are able to spray polymer powder coatings from polyvinyl butyral, polyamide, [5–7]. However, in an oxy-fuel torch fusible polyolefin and secondary polymers degraded; therefore, in recent years the most widespread guns operate using air as the oxidizer. [7–9]. Heat distribution modeling [10–11] showed that heat input of the torch should be within a range of $(1–3)\cdot 10^6$ W/m^2 to spray polymer coatings without destruction. This heat range was realized in a flame spraying gun, which allows changing the heat density to spray polymer coatings with a melting point of 365…670 K [12, 13]. The strength of coating adhesion to the substrate is one of the main factors determining the performance of polymer coatings. The aim of the study is to evaluate the influence of the air-fuel ratio of the torch, the polymer type, the polymer powder particle size, and the share of inorganic fillers in the blend on the adhesion strength of the coatings.

EQUIPMENT AND MATERIALS

A TERKO-P thermal spray gun [12, 13] was used. It allows regulating the heat exchange in the "torch – polymer particle" system by changing the ratio between the combustible mixture exit from the central nozzle (V) and the concurrent airflow (V_g). Changing results are visible as a flame shape change (Fig. 1). Therefore, spraying coatings of low thermal destruction from polymer powders of the (360…650) K melting point and a feed rate up to 2.9 kg/h is possible. The maximal pressure (MPa) of gases is the following: 0.5 (air), 0.2 (propane). Polymer powders were prepared from polymer pellets, secondary polymers and synthetic fiber wastes by cryogenic crashing.

Mechanics, Resource and Diagnostics of Materials and Structures (MRDMS-2016)
AIP Conf. Proc. 1785, 030011-1–030011-4; doi: 10.1063/1.4967032
Published by AIP Publishing. 978-0-7354-1447-1/$30.00



$V < V_g$ (a) $V = V_g$ (b) $V > V_g$ (c)

FIGURE 1. Torch shape depending on the degree of gas-dynamic activation

The following polymer powders were tested: polyamide (PA), high-density polyethylene (HDPE) and polyethylene terephthalate (PETP). The following components were added to the polymers: 200…300 μm glass-ceramic (GC), 25…50 μm aluminum powder (Al). The thickness of the coatings was 0.5…1 mm.

The adhesion strength of the coatings was evaluated by the method of separation of a conical pin [14]. According to a schematic view of the test (Fig. 2), a washer 1 serves as the basis; a pin 2 is inserted into its hole so that its end surface is flush with the external plane of the washer. The total surface of the pin and the washer after preparation is coated with a coating 3. The test consists in pulling the pin by applying a force (*P*). The pin and the washer were made from low carbon steel like C1020 ASTM. The results were averaged for five samples.

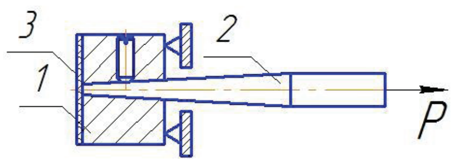
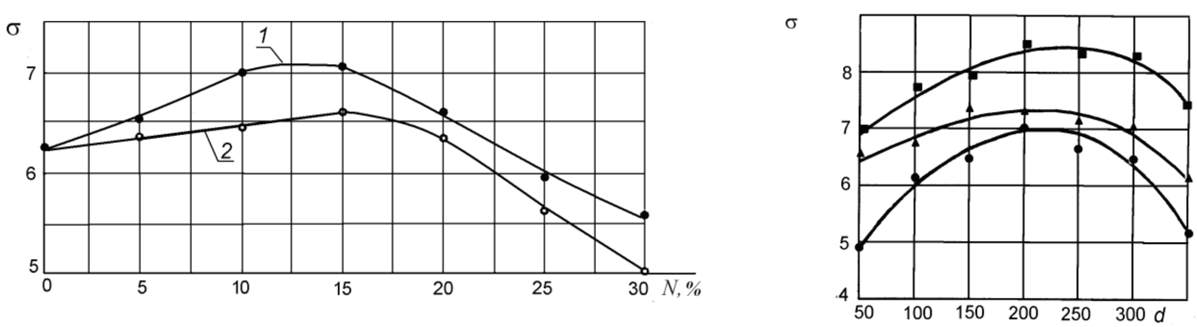


FIGURE 2. Scheme of conical pin separation

RESULTS AND DISCUSSION

The adhesion strength of the HDPE + GC/Al coating changes due to the filler share (5…30 vol. %). The peak value is indicated at 15…20 % of fillers, Fig. 3a.



(a) (b)

FIGURE 3. The change of the adhesion strength σ of a polymer coating (a) due to the share of the filler content (N, vol. %) in the form of glass-ceramic (1) and aluminum powder (2); (b) due to the polymer particle size, PETP (■), HDPE (▲), PA (●)

The adhesion strength of the PA/HDPE/PETP + 10 vol. % Al coating changes due to the polymer particle size. The min/max ratio of diameters is 1.5. The peak value is indicated at the mean particle diameter of 200…250 μm, Fig. 3b.

These results can be explained by the following:

– particles smaller than 50 μm are subjected to burning during spraying; such burning products may be placed on a surface to be coated, and this leads to a reduction of the adhesion strength;

– a particle has no time to melt by the heat of the torch if its size exceeds 300 μm. The presence of incompletely melted particles in the coating-substrate interface also leads to a reduction of the adhesion strength.

Thus, the use powders of a uniform particle size improves adhesion strength. The results of experimental studies have shown that the maximum adhesive strength is observed when the (max particle diameter, d_{max})/(min particle diameter, d_{min}) ratio is less than 1.8…2.0 (Fig. 4a). Polymer powder sizes range from 100 to 300 μm.

In addition, the studies have shown (Fig. 3b, 4a) that coatings based on PETP have the highest adhesion strength of the three types of polymer powders tested. As noted in [1], there is a certain correlation with the adhesion energy of the molecule bond in the polymer (cohesive energy). The higher the energy of cohesion of the functional groups of the polymer, the higher the adhesiveness. PETP, due to the presence of high-energy functional groups, has the highest adhesion.

As is known, the adhesion strength of polymer coatings with a surface of mild steel drastically increases when oxygen-containing groups appear in polymers (– OH, – COOH etc.) [1, 16].

Flame, depending on the share of the combustible gas in the gas mixture, obtains an "oxidizing", "normal" or "reducing" mode [15]. Normal flame is formed by combustion of the stoichiometric mixture of air-fuel, when all of the hydrocarbon molecules are reacted with oxygen molecules. Oxidizing flame is formed by combustion with excess oxygen in the mixture. An excess of the fuel gas forms reducing flame. Oxidizing flame has a limit of oxidant concentration above which the combustion process is terminated.

For gas-flame sets, the lower limit of the reducing propane-air flame is 16 volumes of air per 1 volume of propane (the oxidizer-to-fuel ratio β = 16). With a further decrease in the air content, there is a large amount of unreacted carbon. The upper limit of the oxidizer-to-fuel ratio is (β = 32). The subsequent increase of the oxidant leads to the disruption of the flame.

The adhesion strength of the PA coating changes due to the oxidizer-to-fuel ratio and particle size. The tests show that its highest value is obtained at oxidizing flame (β = 22…32) and with smaller particles (Fig. 4b). This results from the largest specific surface area of the particles-air interaction oxygen, which promotes the formation of a significant number of oxygen-containing groups.

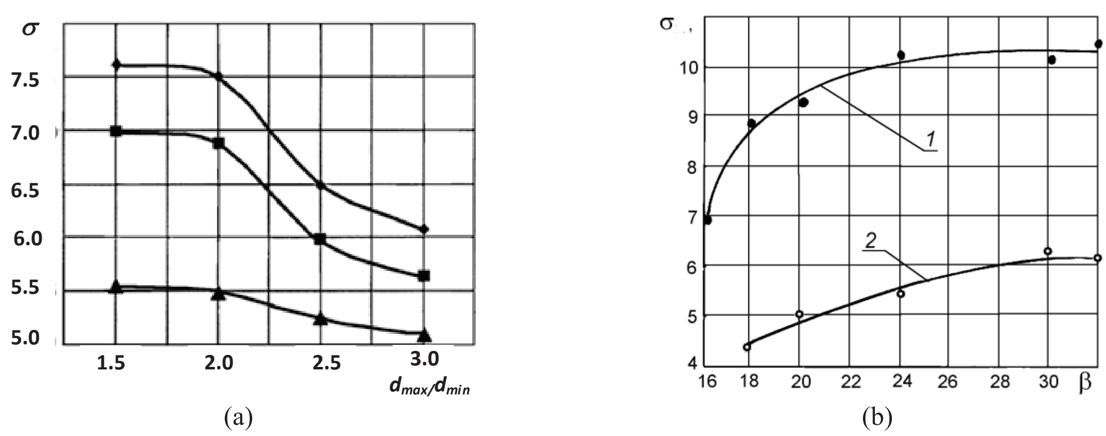


FIGURE 4. The change of the adhesion strength σ of a polymer coating (a) due to the d_{max}/d_{min} ratio (the filler content is 10 vol.% Al), ♦ –PETP; ■ –HDPE; ▲– PA; (b) due to the composition of the combustible mixture, PA – HDPE 50/50, particle size 50…60 μm (1) and 100…200 μm (2)

Thus, various stages of the process require various modes. Spraying of the underlayer should be performed with a powder of particles smaller than 60 μm, β = 24…32. Spraying of the base coating should be performed with a powder of particles sized 100...300 μm, β = 20…24. In this case, a significant oxidation of the coating material, which may cause some reduction in polymer properties and adversely affect the adhesion, is eliminated. Melting of the coating should be carried out at β = 16…20 to exclude oxidation, which can be realized by reducing flame treatment.

CONCLUSIONS

1. The following polymers have been tested: high-density polyethylene, and polyethylene terephthalate. Polyamide has the highest adhesion strength due to high-energy functional groups.
2. A maximum adhesion strength can be imparted to various polymeric coatings by spraying powders with a particle size of 150…300 μm, and the ratio between the minimum and maximum diameters of the particles should be less than 2.0.
3. Inorganic fillers in the polymer powder allow adhesion strength to be increased by 15–20 %, and the peak value of the filler content is 15 vol. %.
4. To get the highest coating properties, the process should be divided into stages of spraying an intermediate layer, a base layer and melting, which differ in the size of the powder and the oxidizer-to-fuel ratio.

ACKNOWLEDGMENTS

The study was supported by RFBR project 16-58-48010 IND omi

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